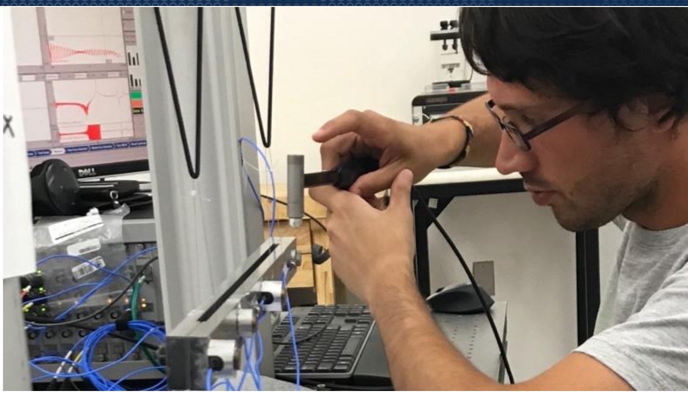

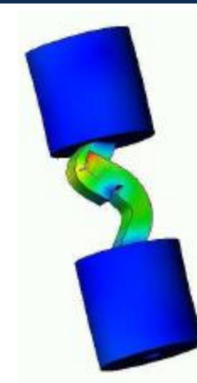

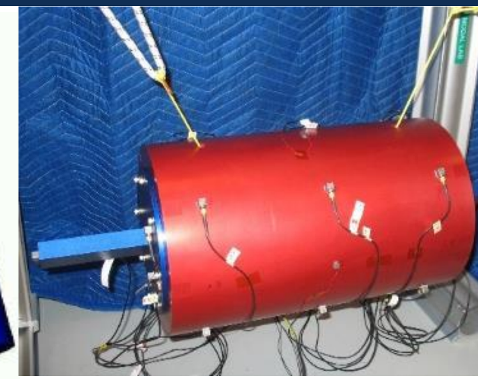

Influences of Modal Coupling on Nonlinear Modal Models

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Phil Thoenen

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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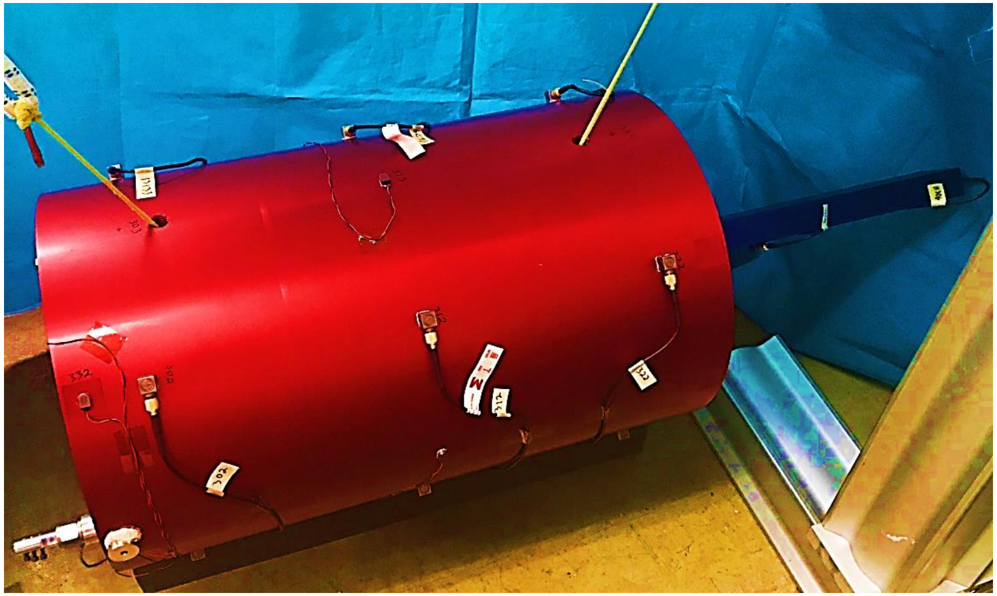
SAND2018-8336 C

Agenda



1. Introduction
2. Project Overview
3. Experimental Methodology
4. Contact Analysis
5. Nonlinear Parameter Characterization
6. Conclusion

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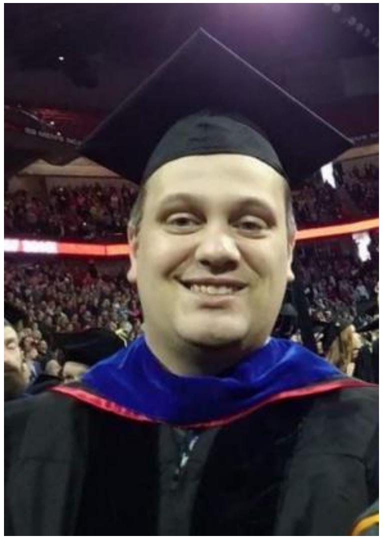

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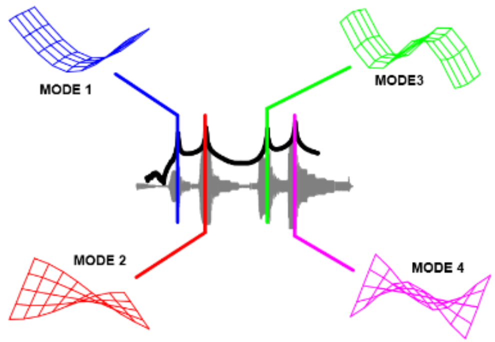
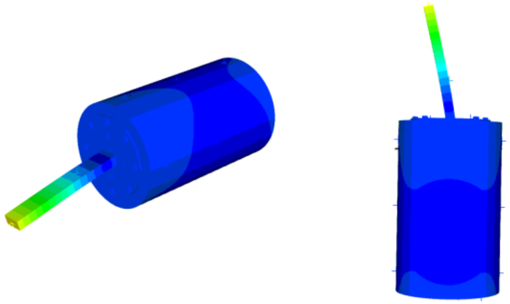
Motivation for Modal Analysis

Characterize dynamics of a system under vibrational excitation



SEM Experimental Techniques - February 1998, P. Avitabile

Determine system natural frequencies and mode shapes



Impact design decisions to avoid failure

Wonderfulengineering.com

Linear vs. Nonlinear Systems

- Linear analysis assumes
  - Amplitude independent modes
  - Modes can be superimposed due to their orthogonality
  - Small deformations
  - Equation:

$$\ddot{q}_r + 2\zeta_r\omega_r\dot{q}_r + {\omega_r}^2 q_r = \Phi^T F_{ext}$$

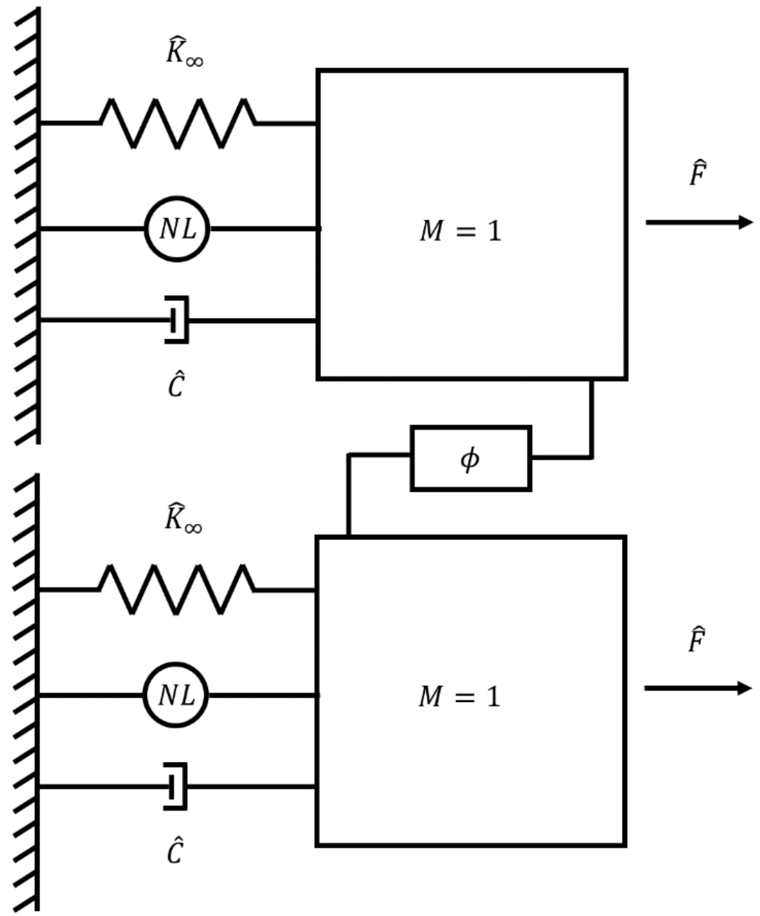
- Psuedo – Nonlinear analysis assumes
  - Linear modes can decouple nonlinear data
  - Little to no coupling between modes
  - No energy transfer between modes
  - Shapes of the linear modes are preserved
  - Equation:

$$\ddot{q}_r + 2\zeta_r\omega_r\dot{q}_r + {\omega_r}^2 q_r + F_{nl}(q_r, \dot{q}_r) = \Phi^T F_{ext}$$

What happens if there is coupling of the modes?

What is modal coupling?

- When the excitation of one mode causes a transfer of energy that perturbs another mode
- Usually occurs due to interactions at joints shared by the different mode shapes



Objectives

Determine the influences of modal coupling on nonlinear modal models

Excite different combinations of modes on a nonlinear structure

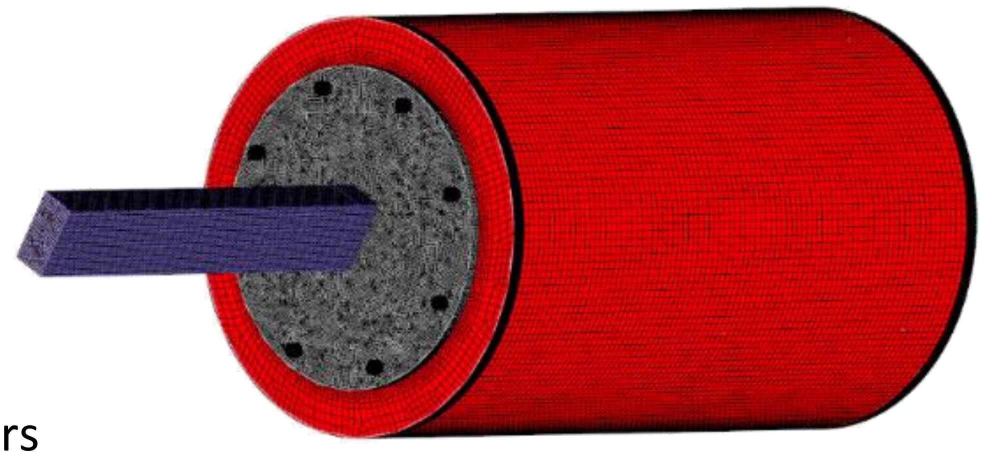
Experimentally identify the presence modal coupling

Create a reduced order nonlinear modal model to match experimental results

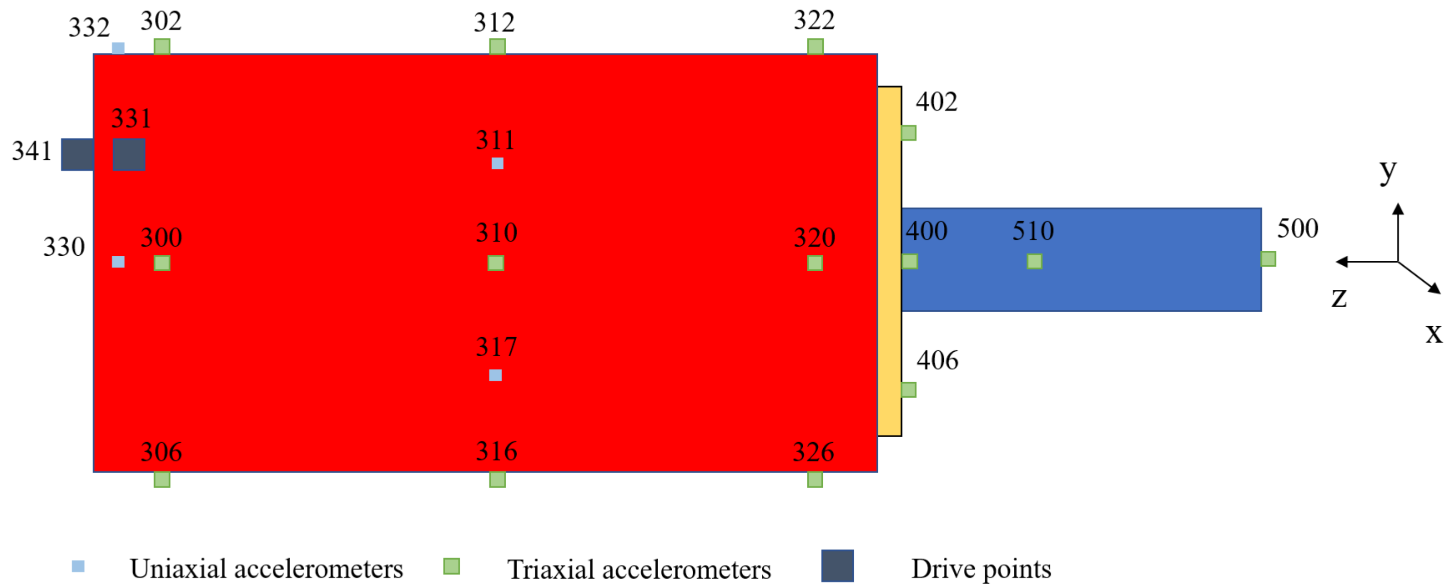
Test System

Cylinder – Plate – Beam (CPB)

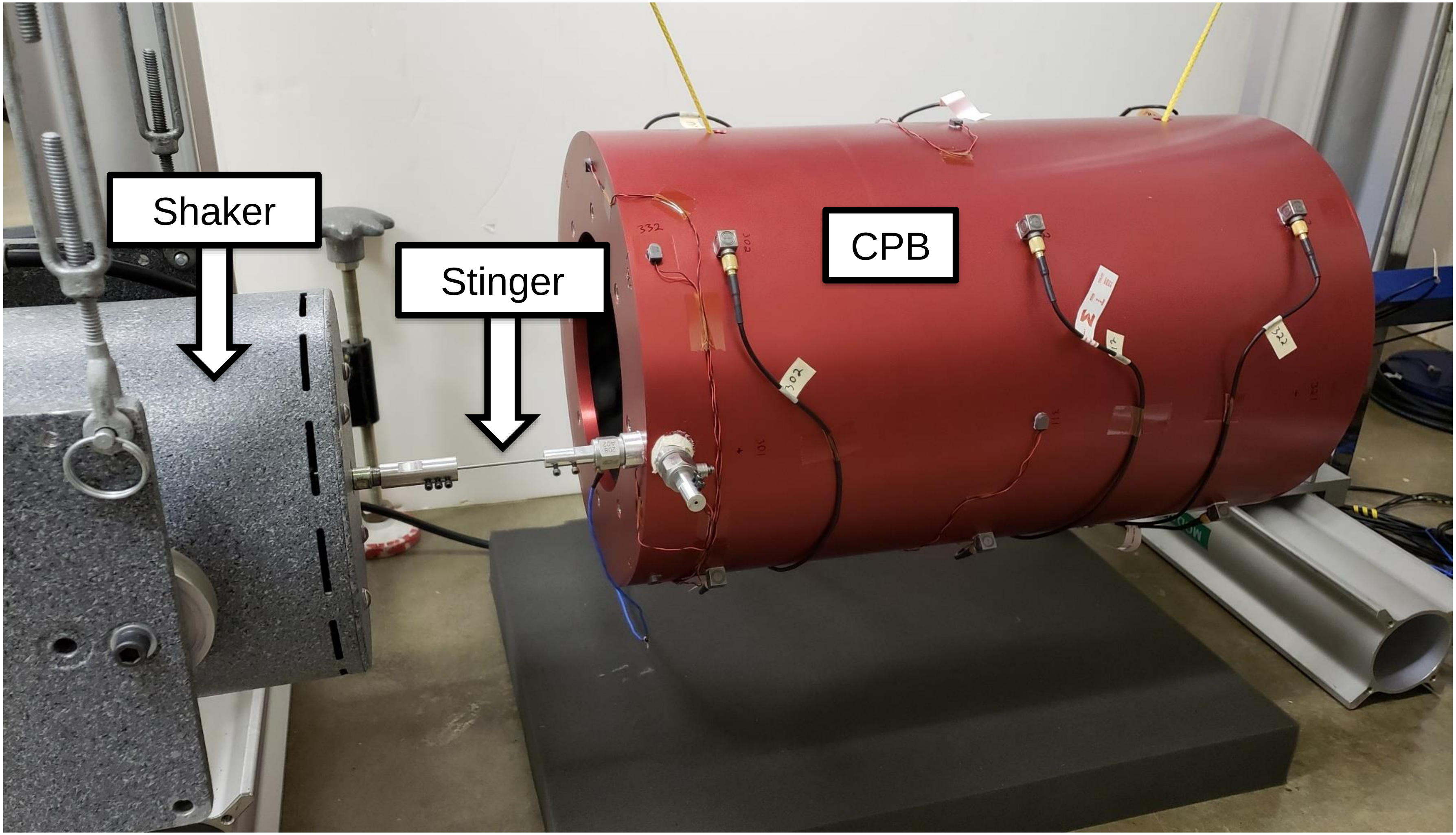
- Plate bolted to cylinder
- Beam bolted and glued to plate



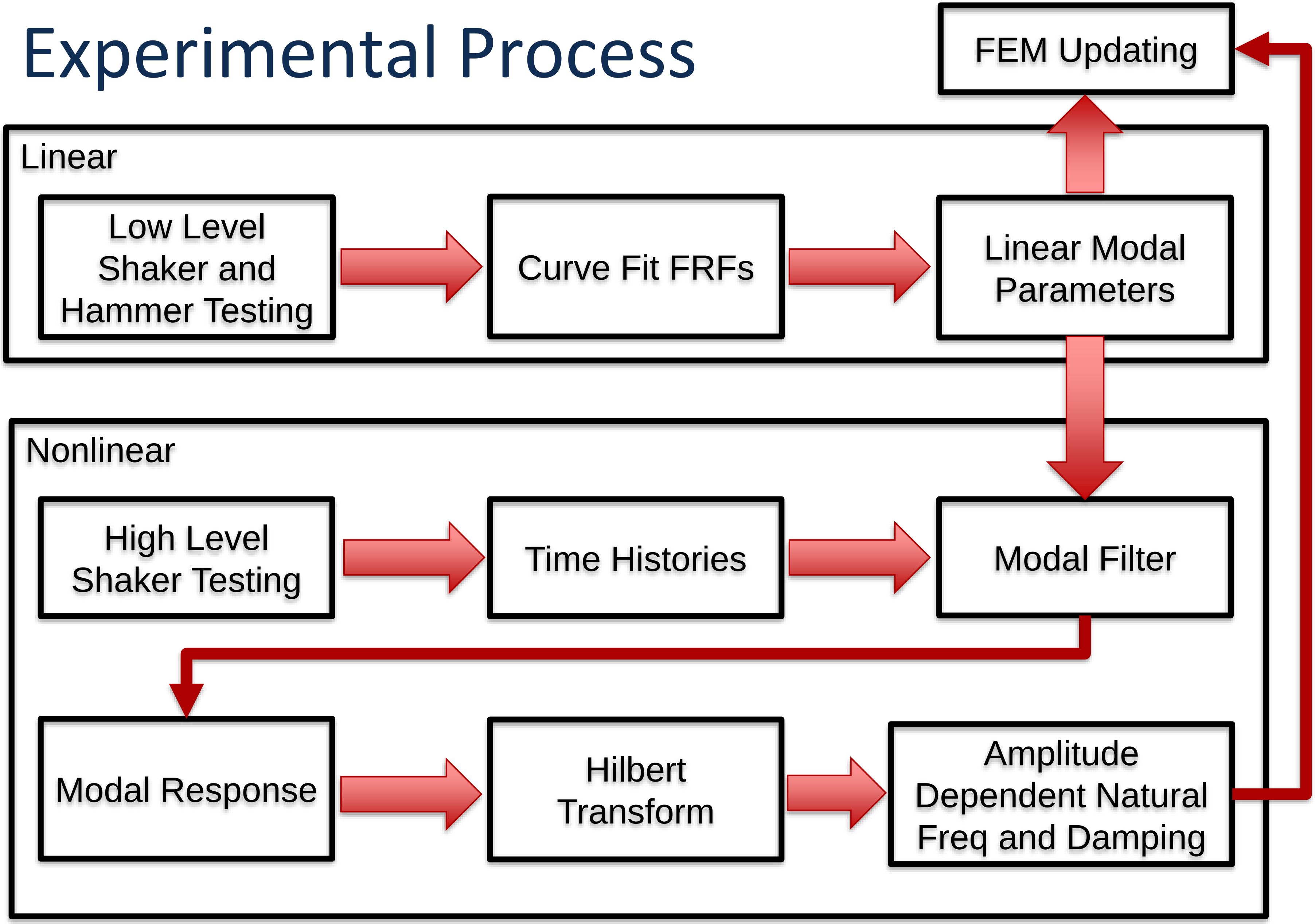
18 triaxial + 8 uniaxial accelerometers



Experimental Setup

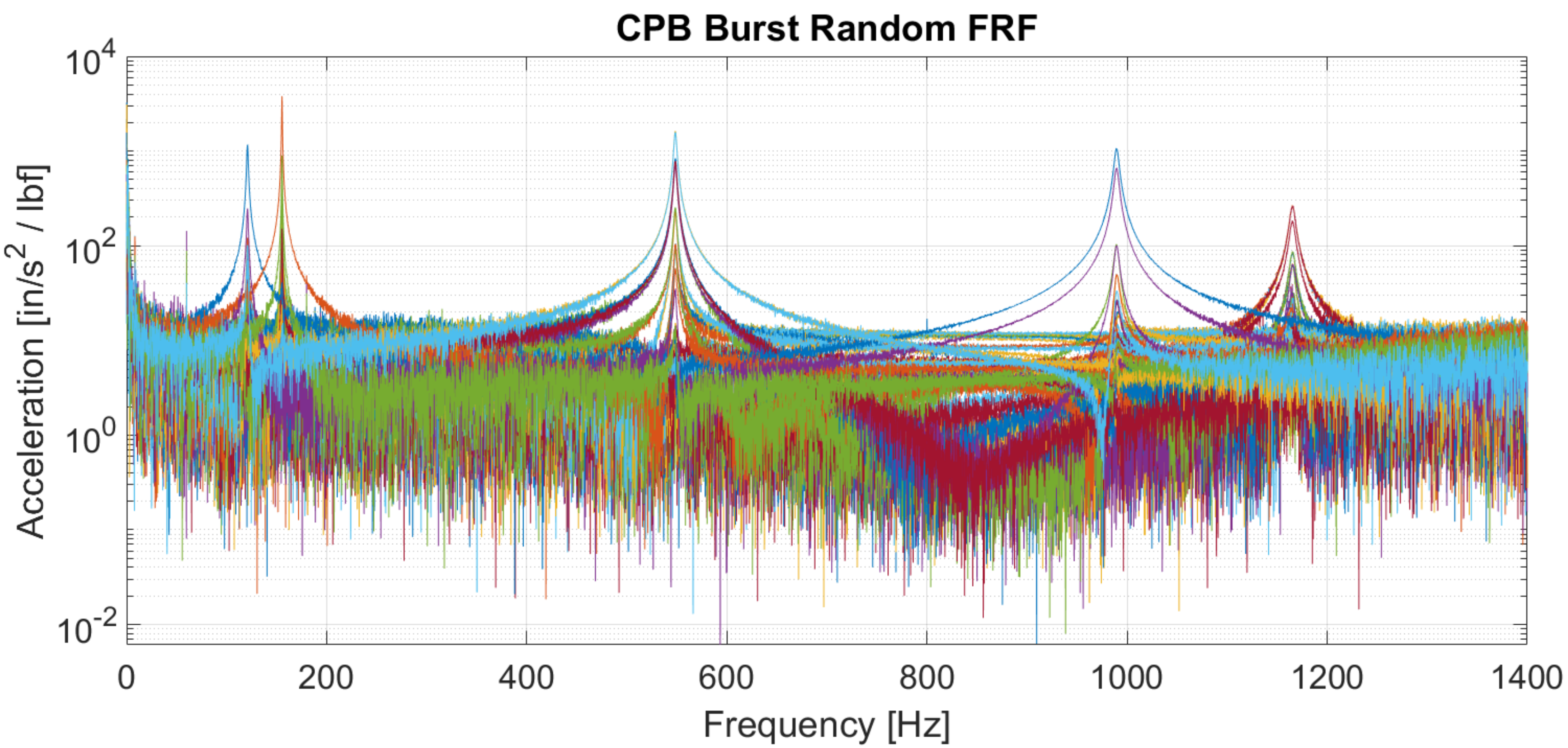


Experimental Process



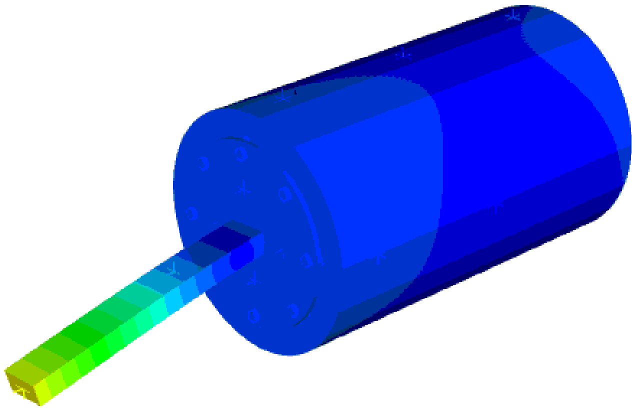
Linear Experimental Data

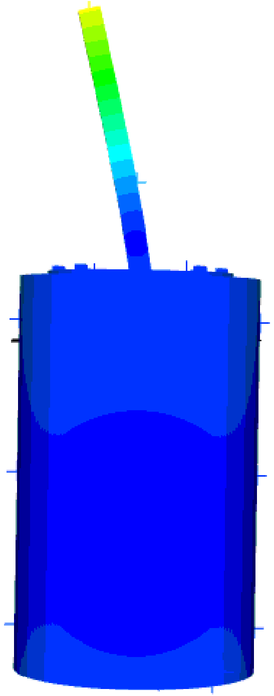
- Beam bending modes from low level burst random shaker and cylinder modes from light hammer hits
  - Natural frequencies for model updating and shapes for modal filtering



Mode 1

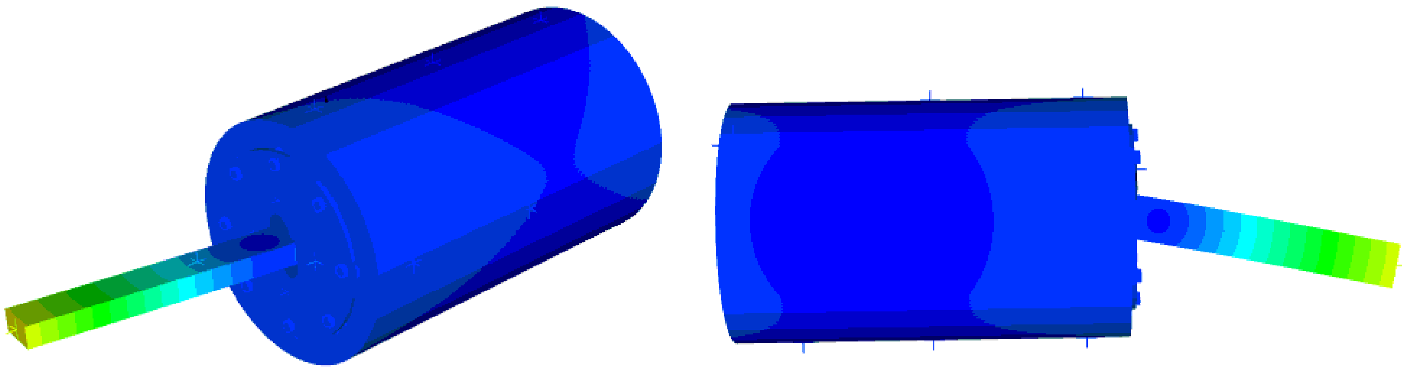
Mode Description	Experimental ω_n (Hz)
1st Beam Bending X	120.8





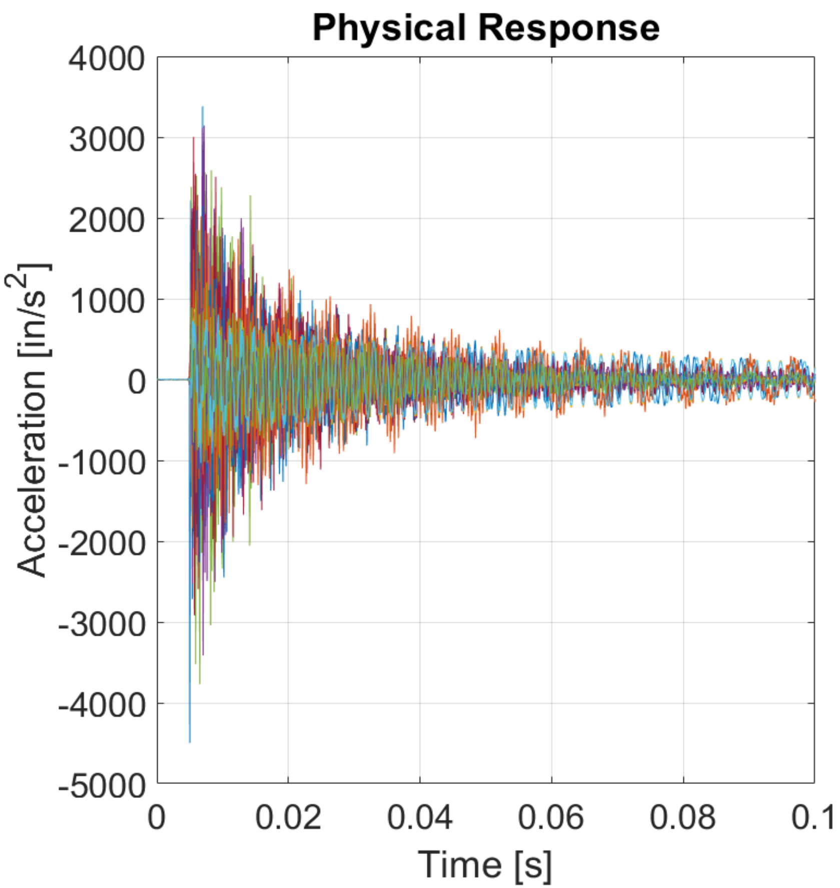
Mode 2

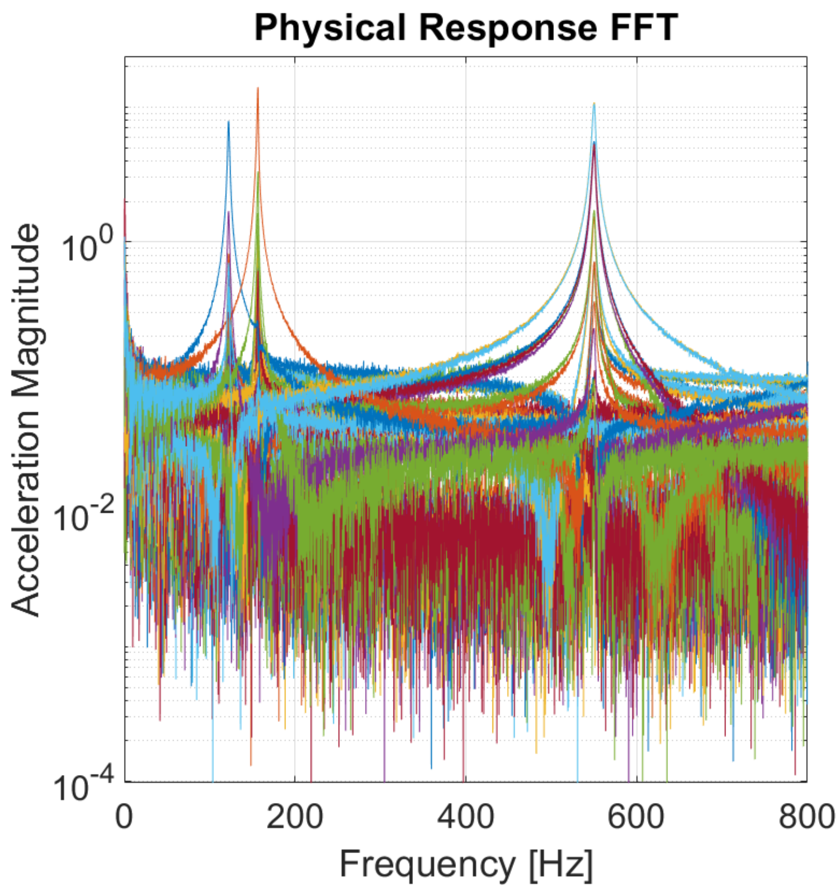
Mode Description	Experimental ω_n (Hz)
1st Beam Bending Y	155.3



Modal Filtering

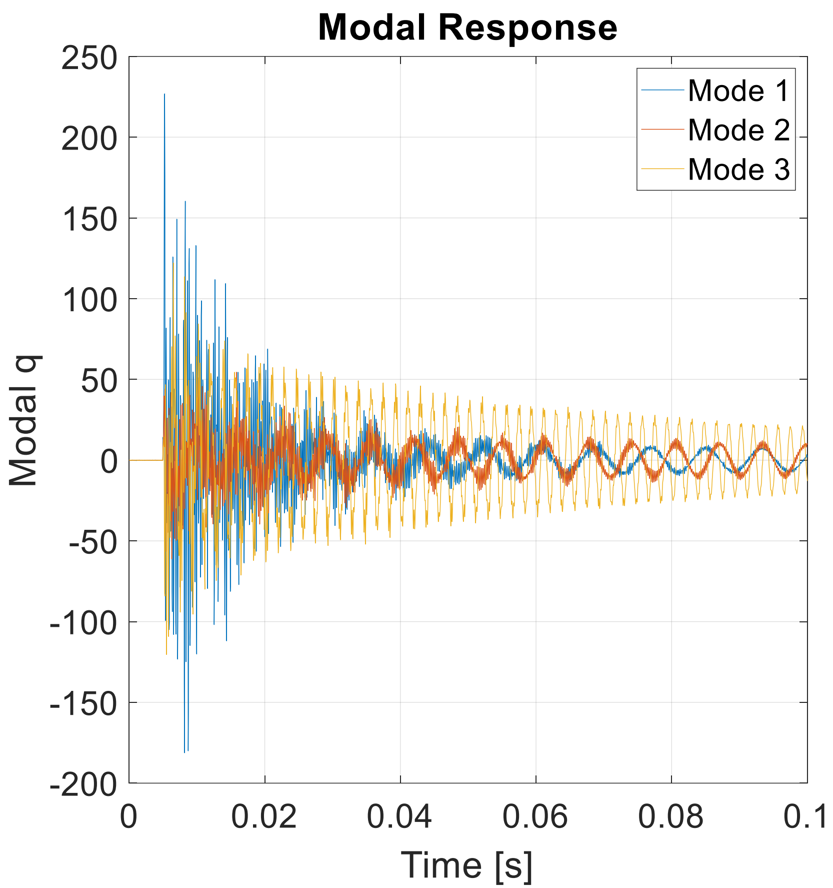
- Linear mode shapes allow for filtering of physical response into modal coordinates

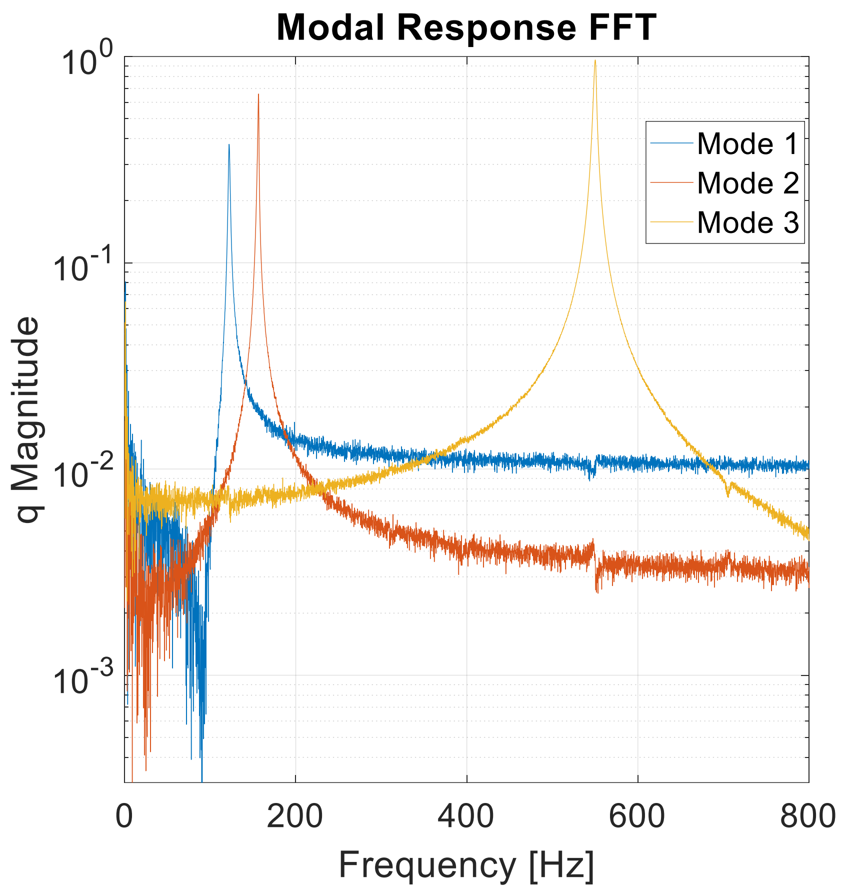




Modal Filtering

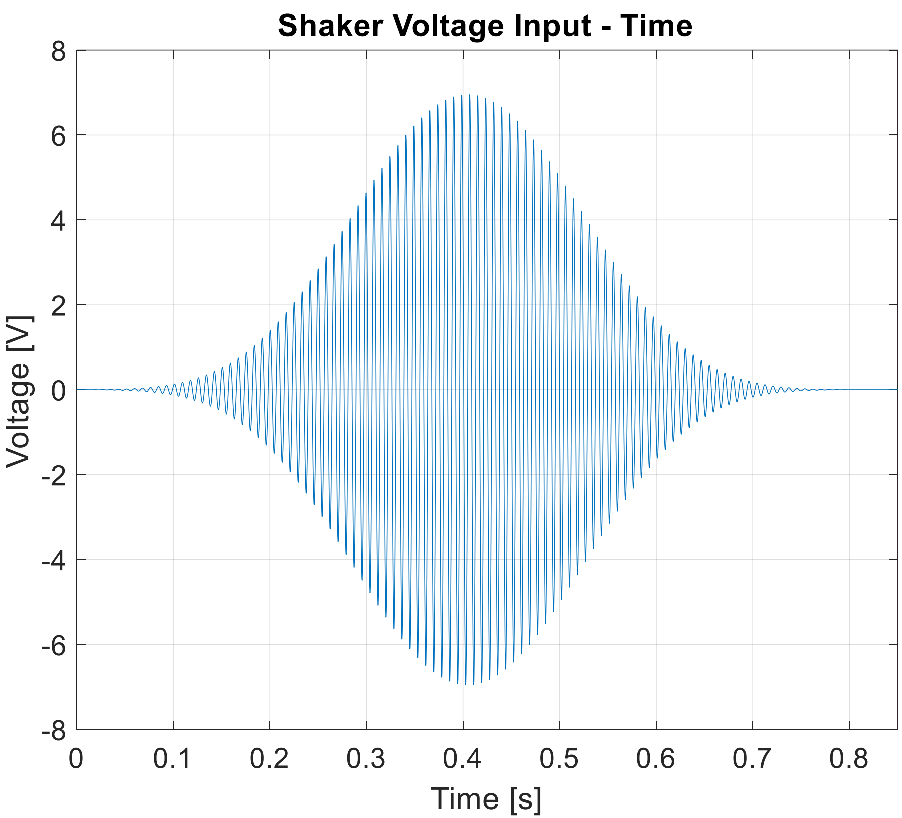
- Linear mode shapes allow for filtering of physical response into modal coordinates

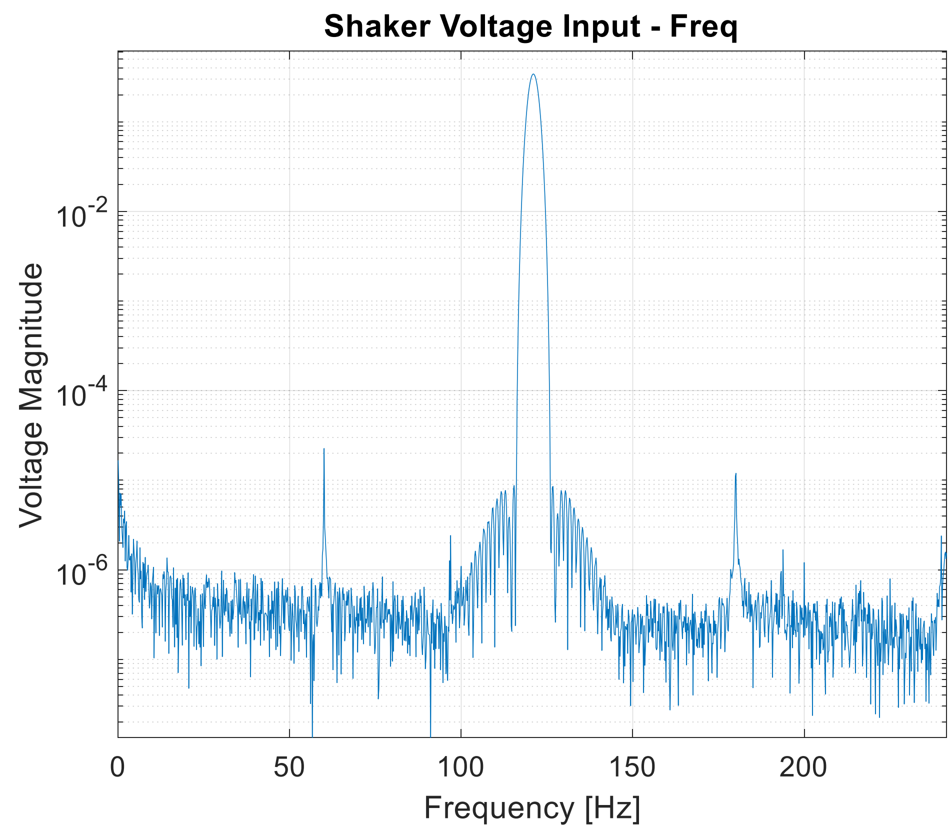




Nonlinear Data

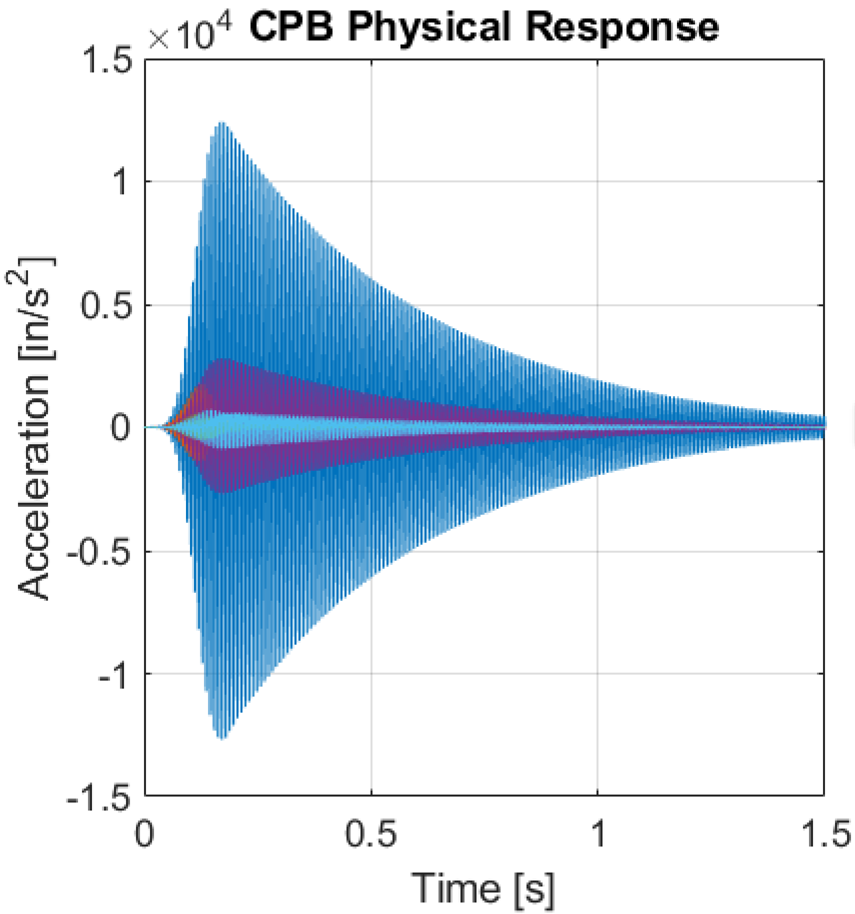
- Shaker delivers definable force input – able to create a voltage signal with specific frequency content

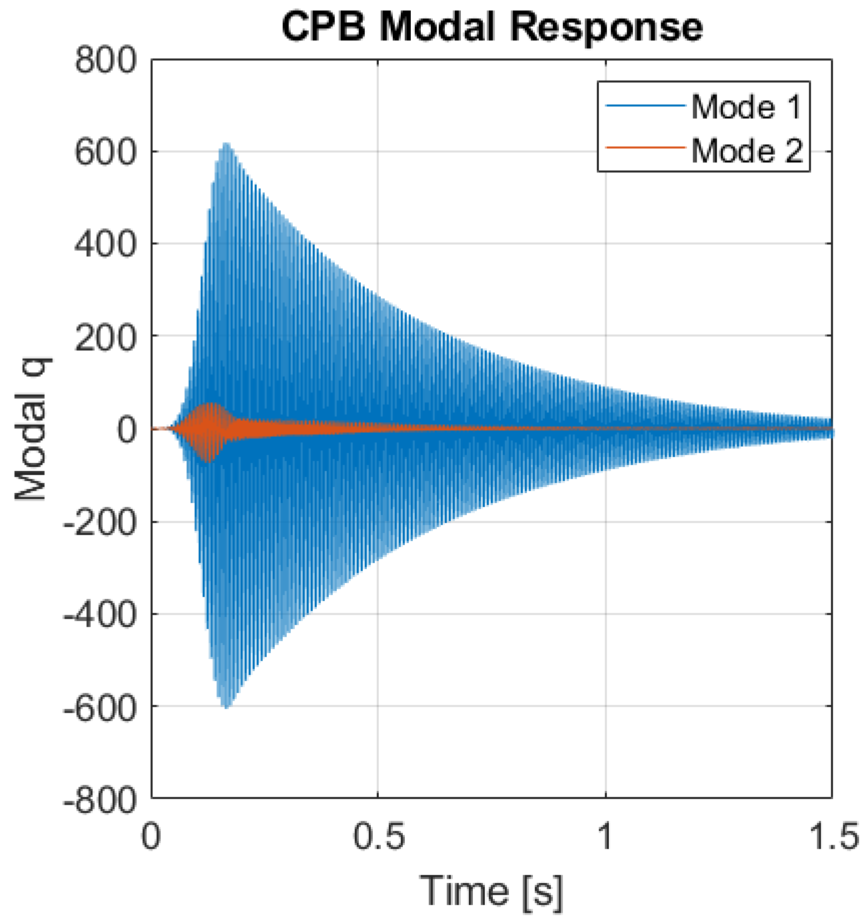




Nonlinear Data

- Use shaker to excite specific modes

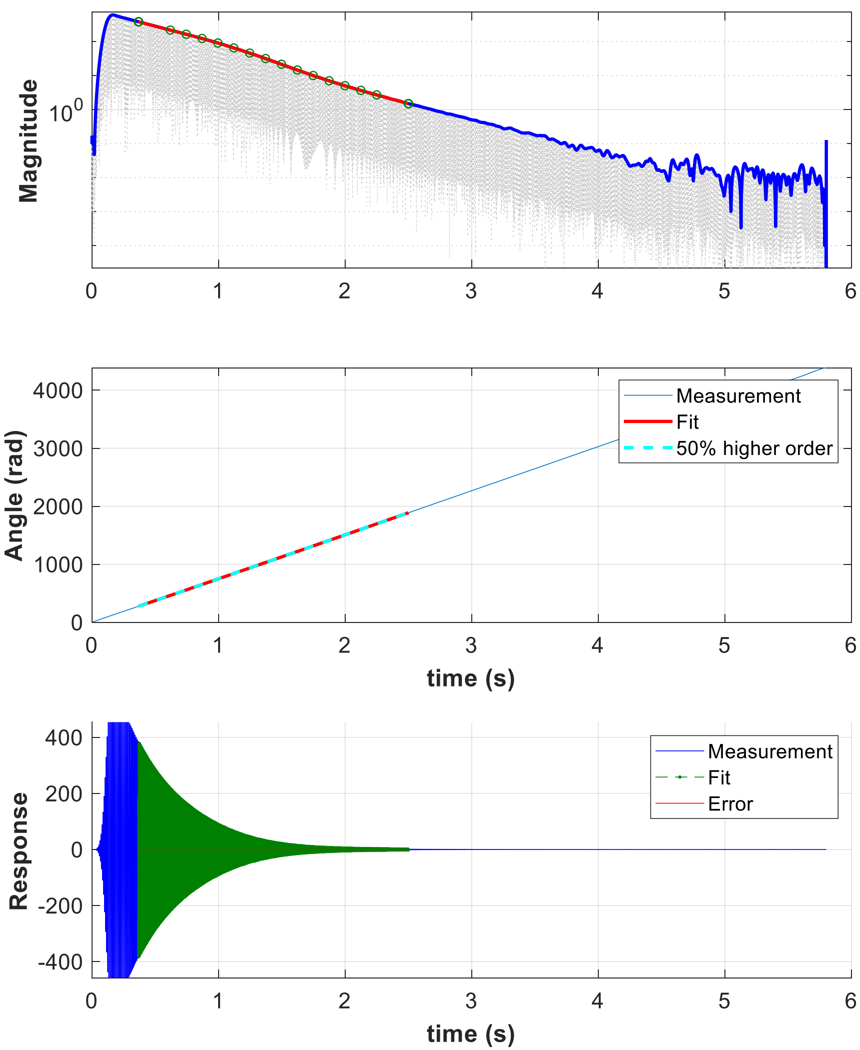


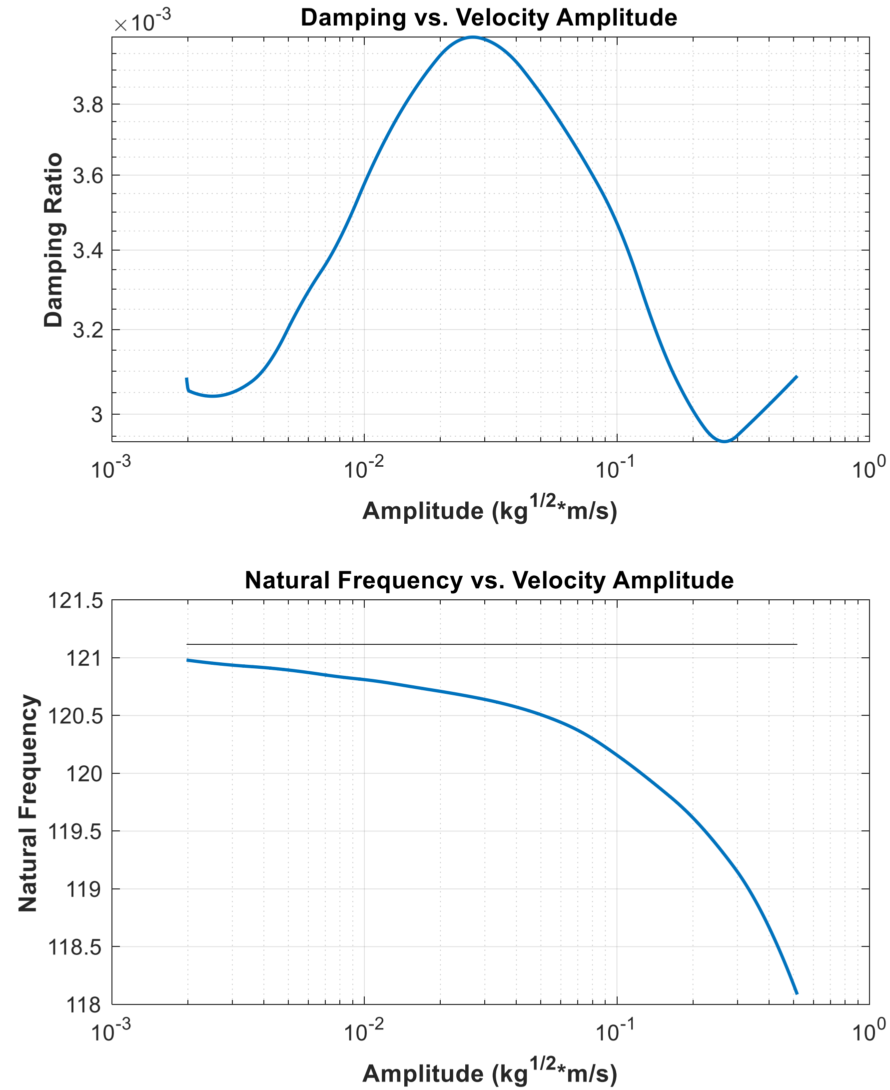


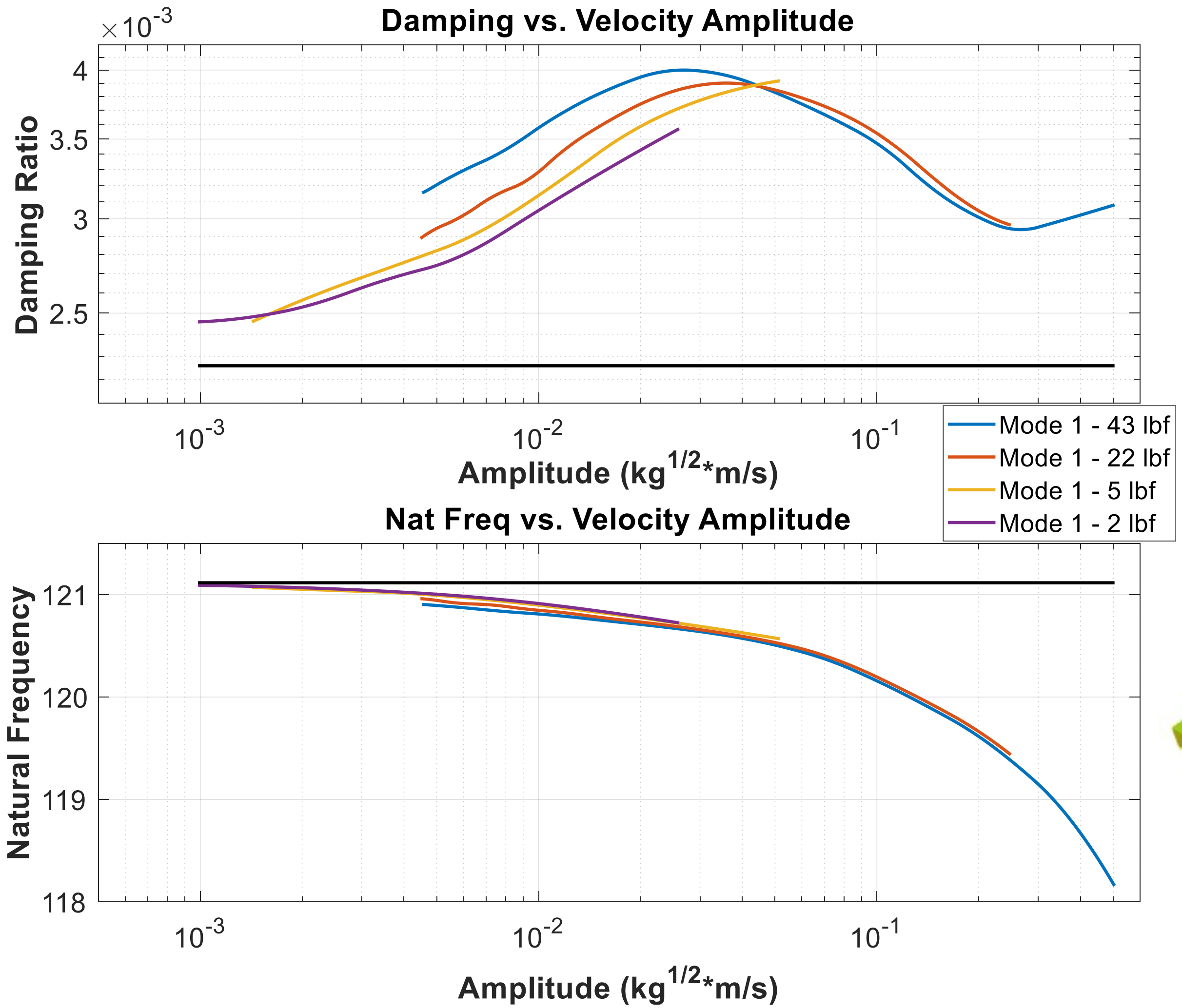
Hilbert Analysis

- Requires that each response be uncoupled such that it can be represented by a SDOF system
  - Signal can be represented by a decaying harmonic
  - $\ddot{\eta} = Re\left[\exp\left(\psi_1(t) + i\,\psi_2(t)\right)\right]$
- Compute Hilbert Transformation ($\mathcal{H}(t)$) for an amplitude dependent representation of damping and frequency
- $\omega_{d,r} = \dfrac{d\psi_2}{dt}$
- $\zeta_r \triangleq \dfrac{d\psi_1}{dt} / \omega_r$

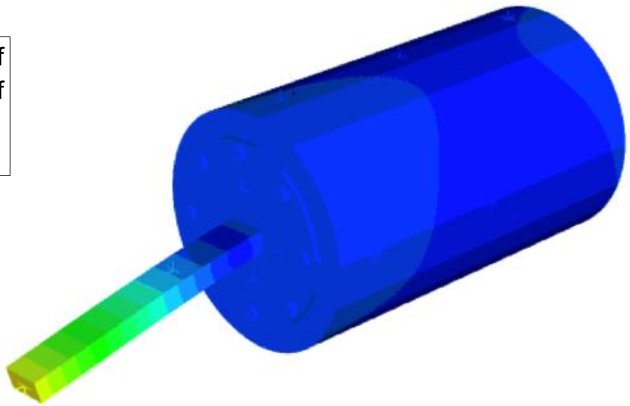
Hilbert Analysis



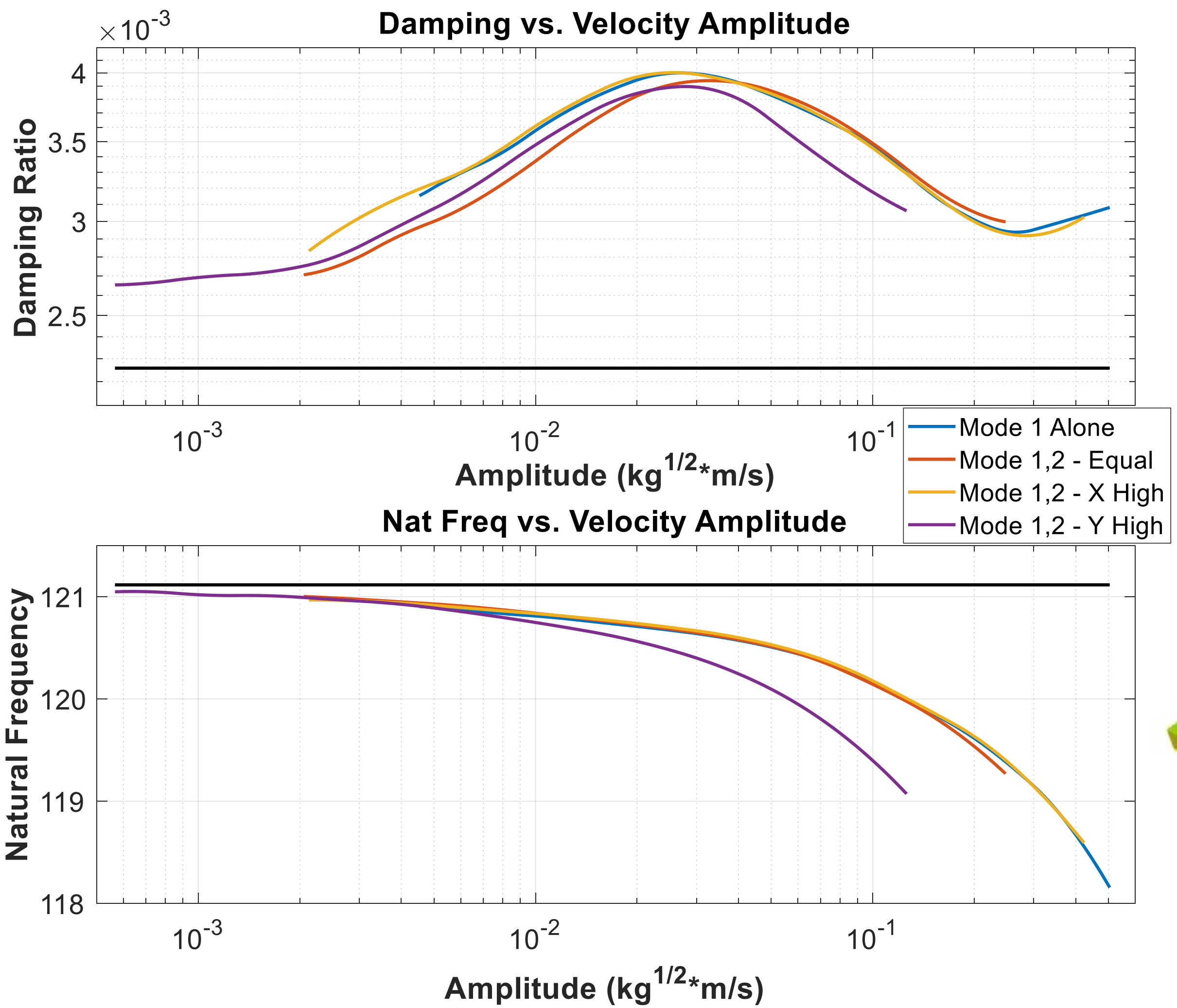




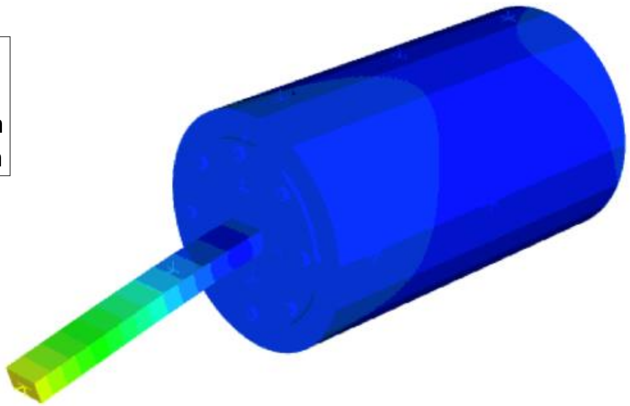
Mode 1



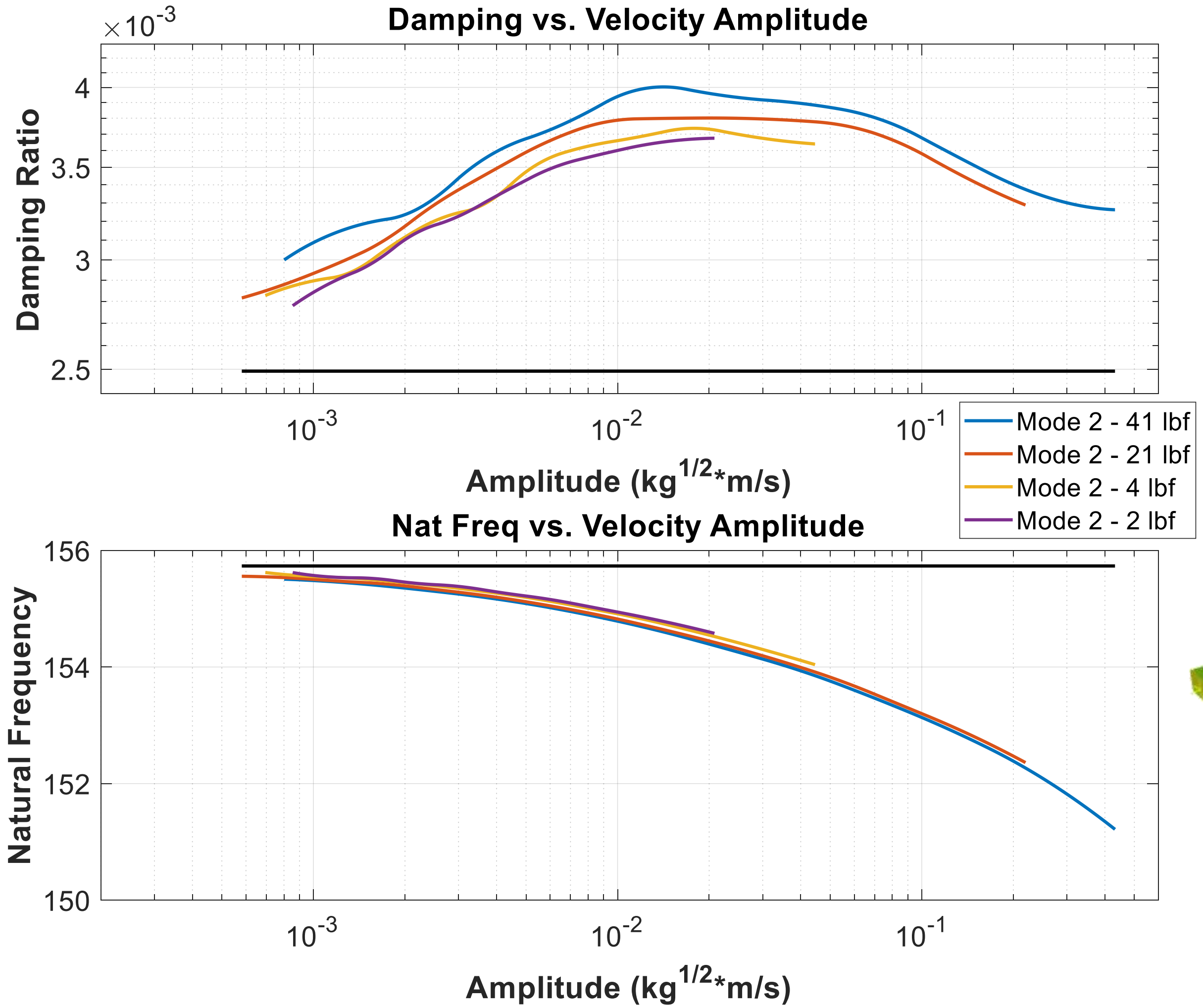
- When excited alone at various levels, frequencies overlay and damping appears to increase with increasing energy



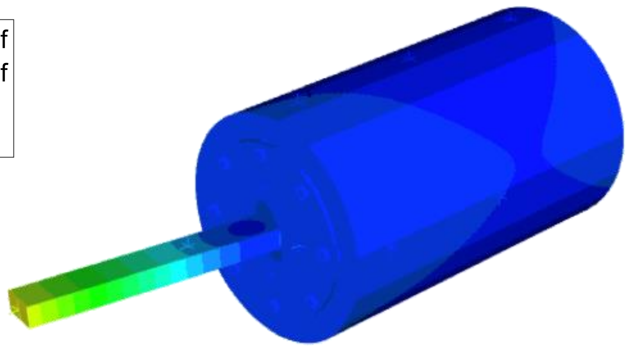
Mode 1



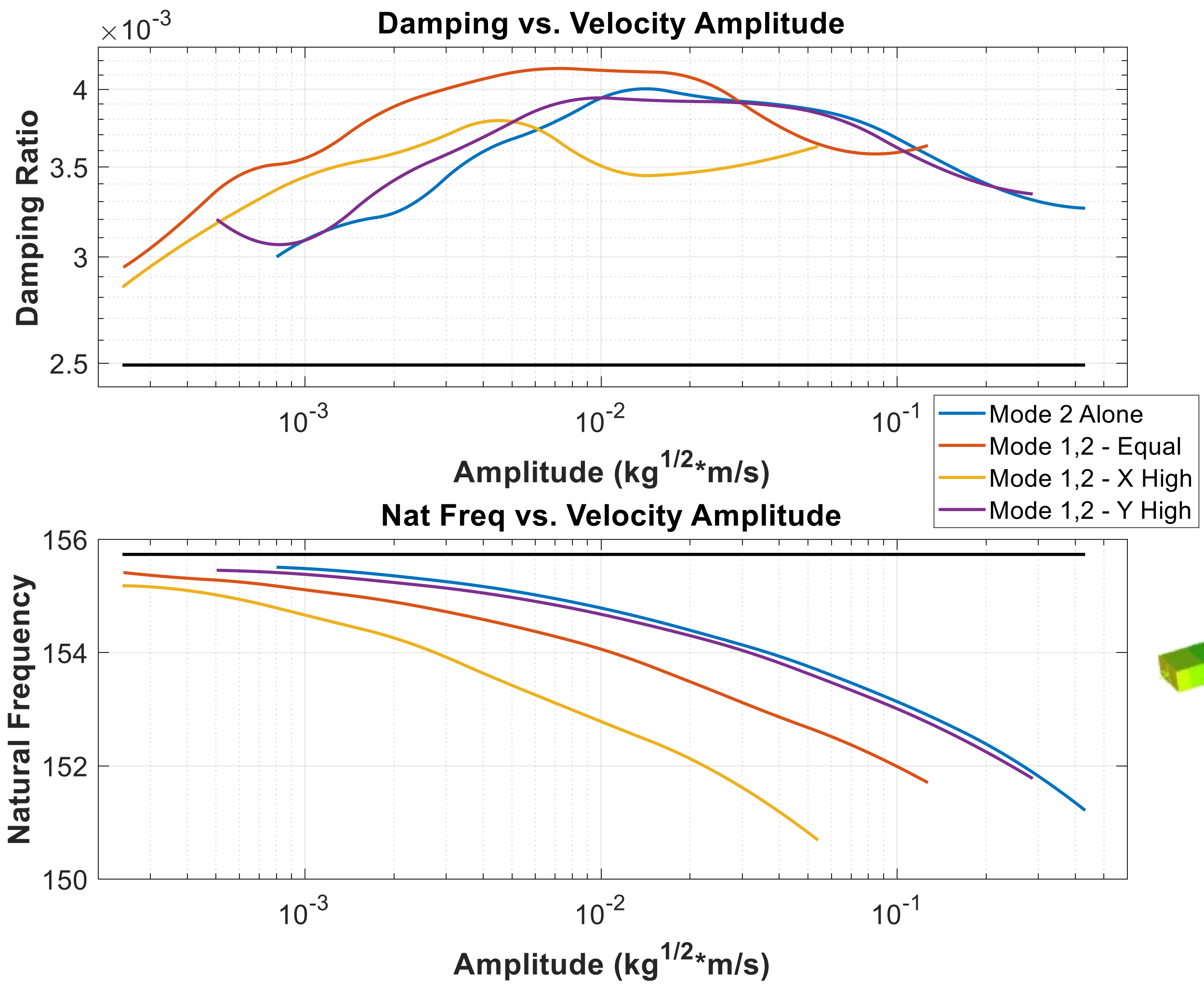
- Coupling visible as a frequency and damping shift when mode 2 is excited to a higher level than mode 1



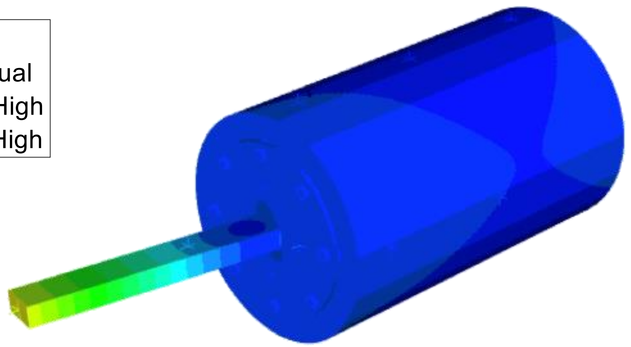
Mode 2



- As with Mode 1, when Mode 2 is excited alone, the frequencies overlay and damping increases with force.



Mode 2

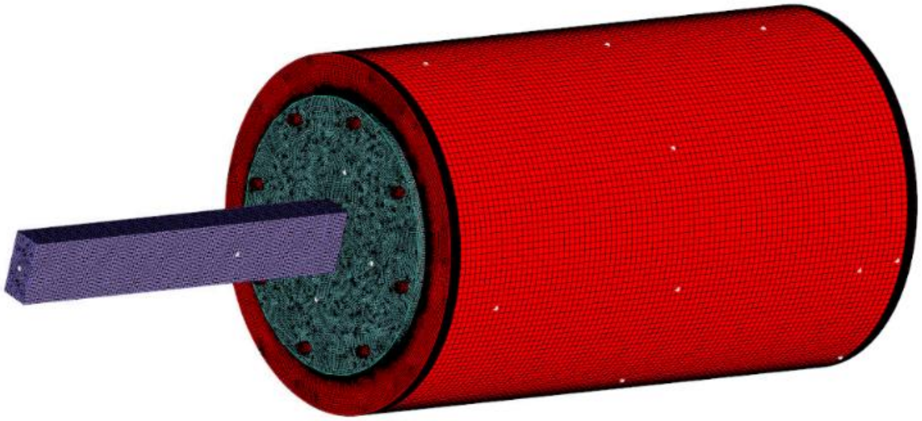


- See same frequency and damping shift, but now to some degree in all cases where mode 1 is also excited.

Model formulation

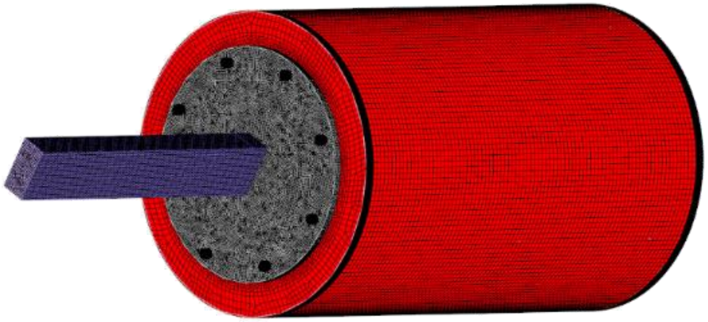
- Developed high fidelity model accounting for entire system geometry

- Updated material properties to match system linear frequencies



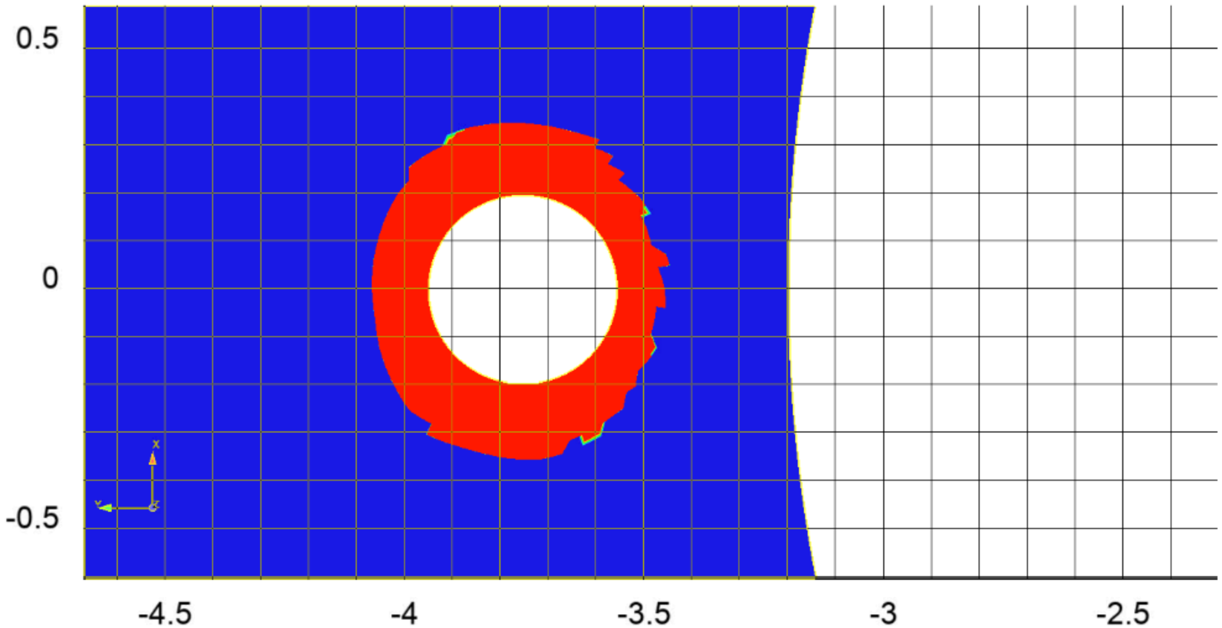
Aluminum	
E_{avg}	10.23 E+6 psi
ν_{avg}	0.34
ρ_{avg}	$2.57\,\frac{lbs-s^2}{in^4}$

Modeling Contact Area



- Bolted structures exhibit slip at the edge of its contact patch
  - This causes hysteresis and an increase in damping
- Primary sources of nonlinearity in the system
  - Opening and closing of the gap between plate and cylinder
  - Joints

Red = contact
Blue = not in contact

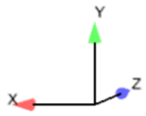


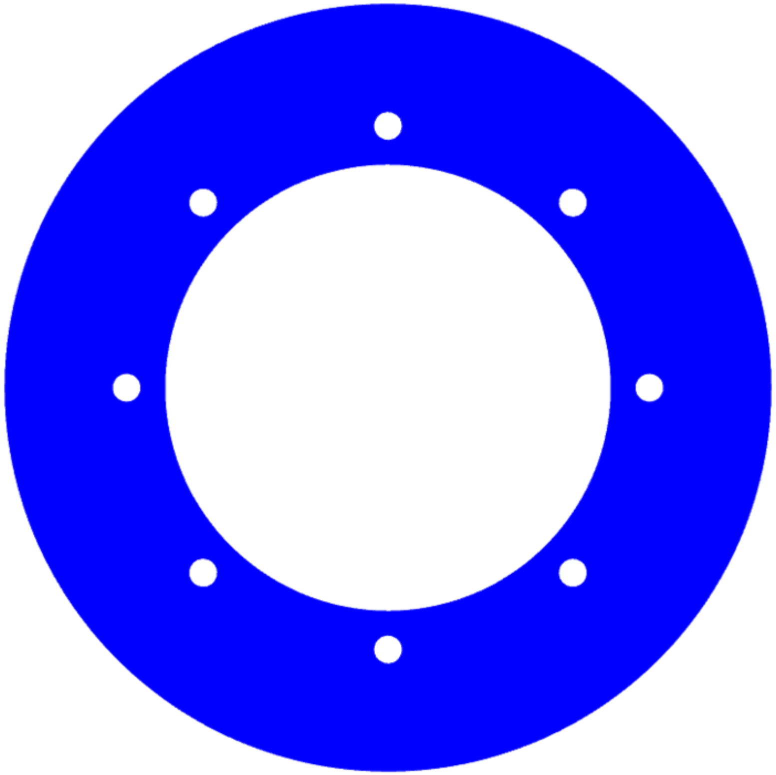
Contact Area

Red = contact

Blue = not in contact

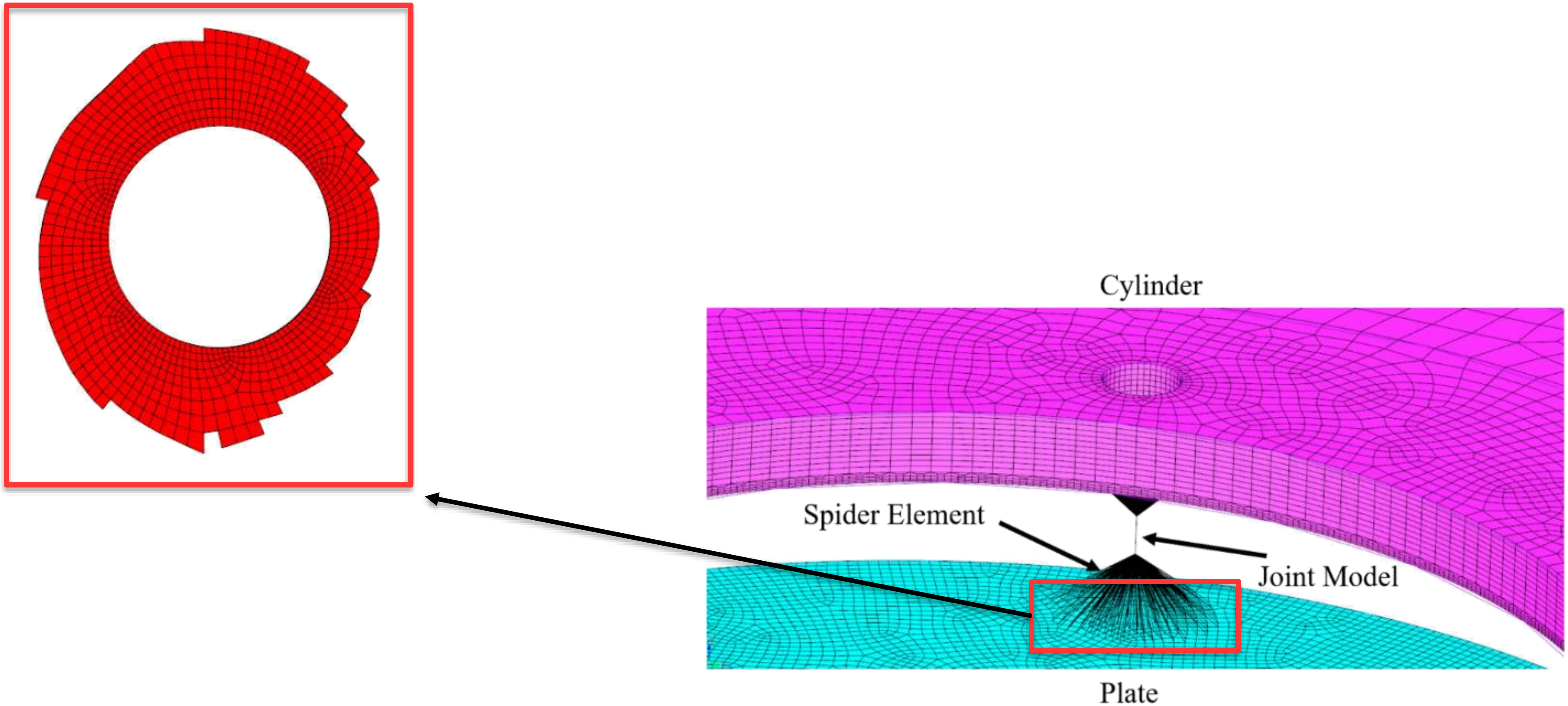
- Pull on bolts with preload force
- Glue bolt threads to bolt holes
- Release preload force on bolts
- Let kinetic energy dampen out





Contact Area to Spidering

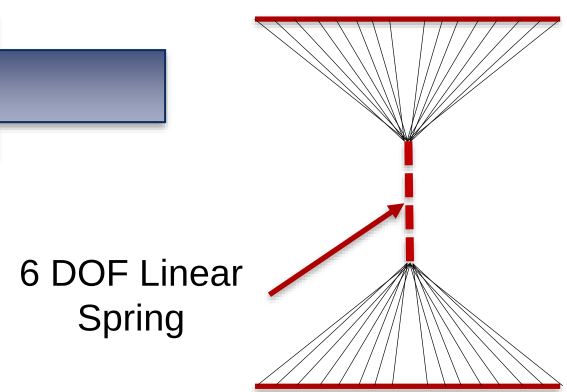
- Spider elements attached to extracted nodes from contact area simulation



Linear Updating

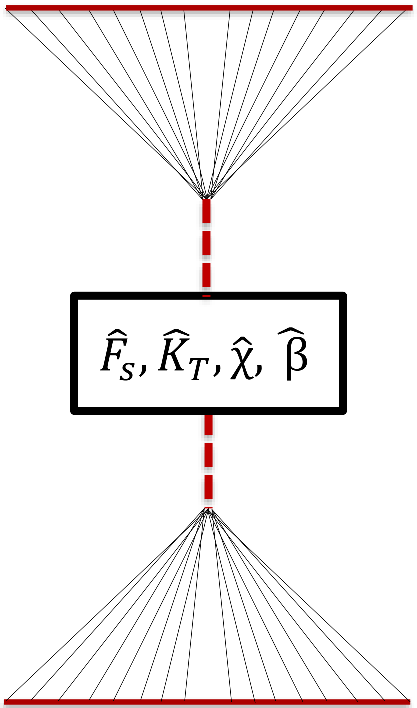
Test Natural Frequencies → Model Contact Area → Monte Carlo Sim. to get Linear Springs

Mode	Experimental f_n $[Hz]$	Updated Model f_n $[Hz]$	Percent Error
1	120.8	120.1	-0.63
2	155.3	154.5	-0.56
3	548.4	548.7	0.04
4	989.5	967.9	-2.18
5	1165.1	1168.8	0.32
6	1165.6	1170.4	0.41

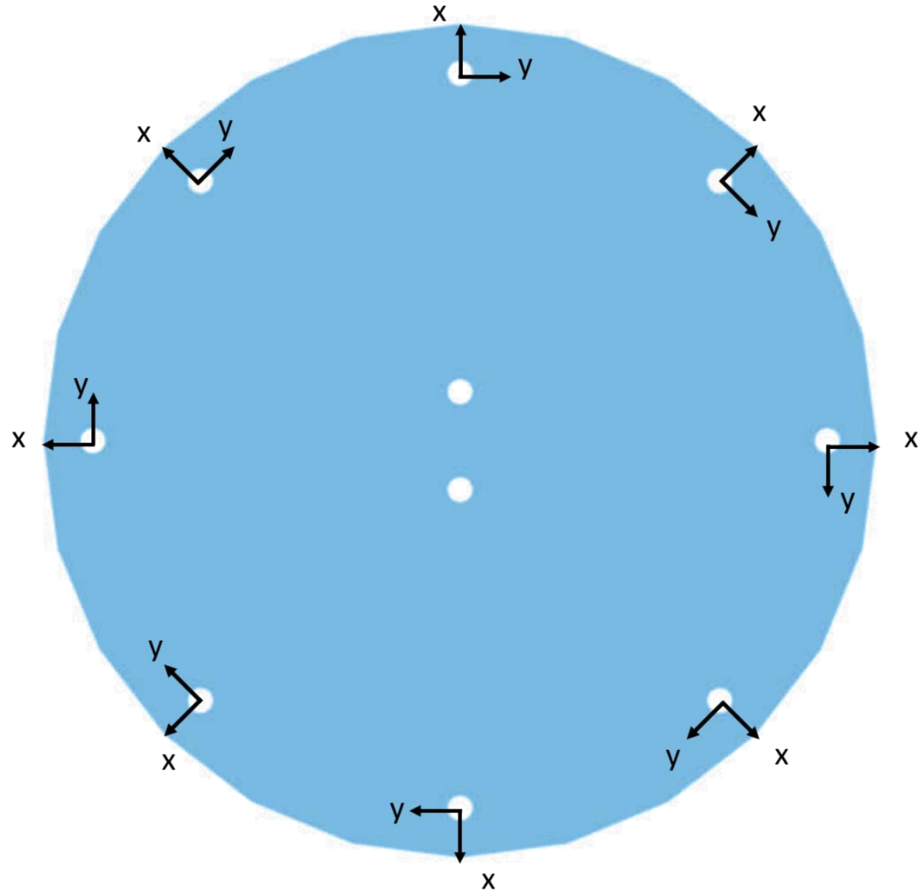


Iwan Parameterization

- Constitutive joint model to describe metal elasto-plasticity behavior
- Each Iwan Joint is comprised of four physical parameters
  - F_S Force required to cause slip
  - K_T Joint stiffness when no slip occurs
  - χ Exponent describing the slope of energy – dissipation curve
  - β Shape parameter of the energy – dissipation curve near macroslip



Iwan Parameterization

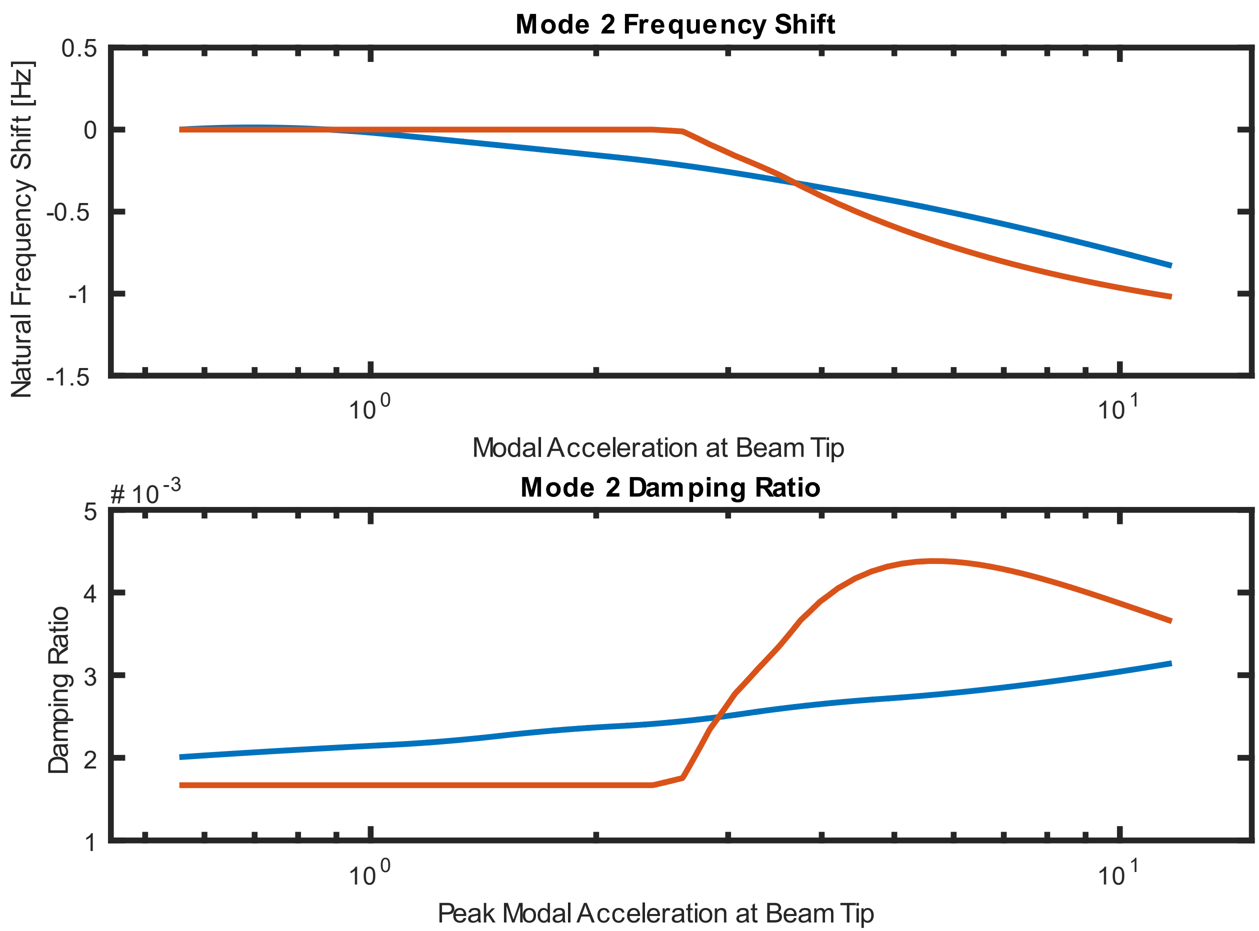


Model directions of slip with Iwan Joints

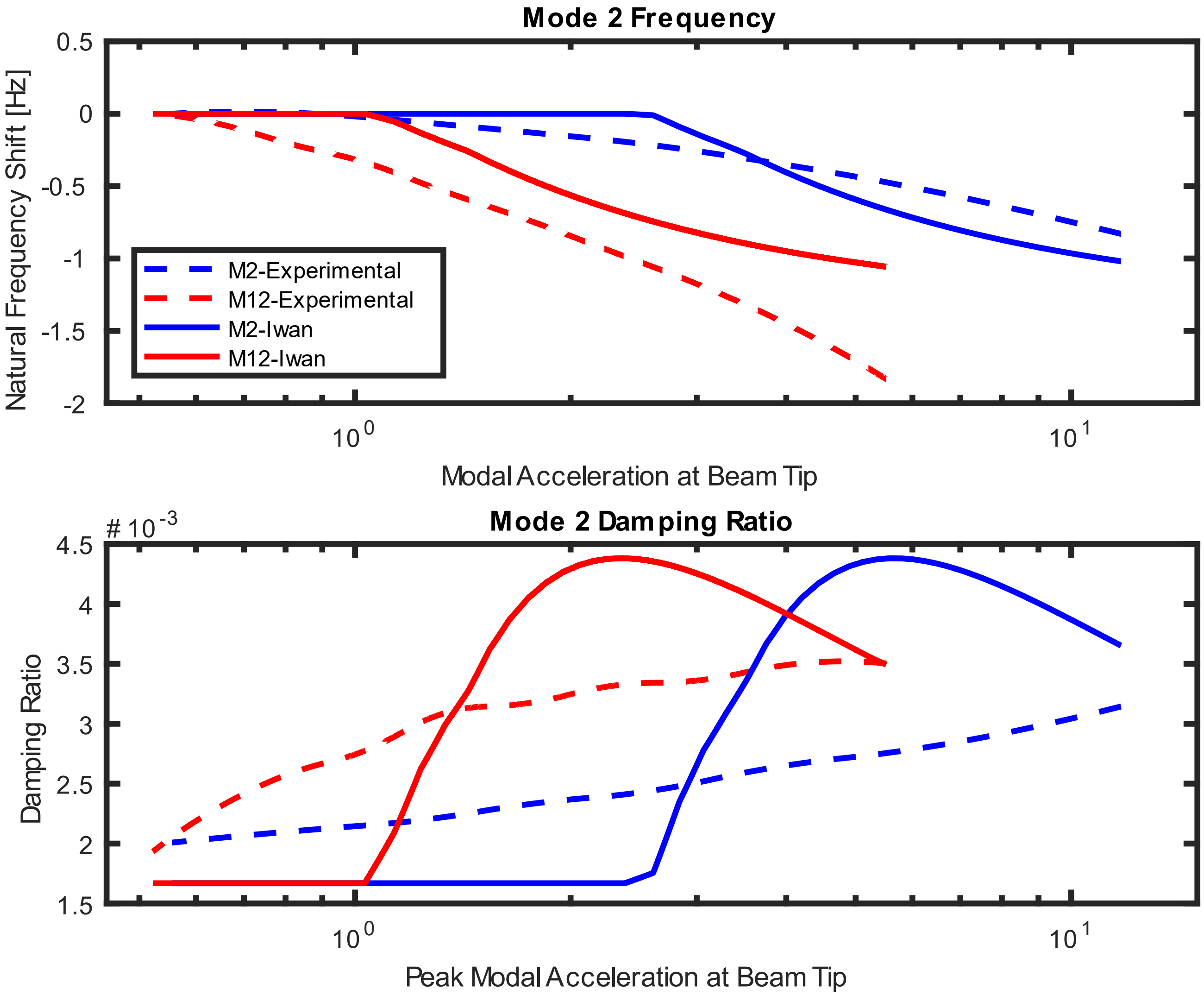
(Radial and Tangential on Cylinder – Plate Interface)

Iwan Mode 2

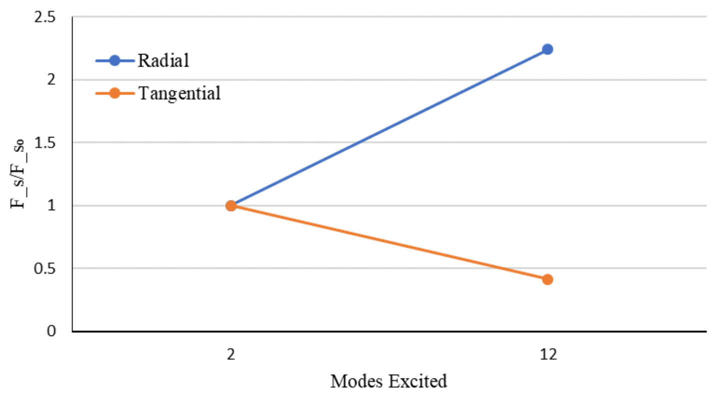
Joint	F_s	K_T	χ	β
Radial	2104	2.26E+05	-0.237	5.51
Tangential	0.199	2.15E+12	-0.692	9.37

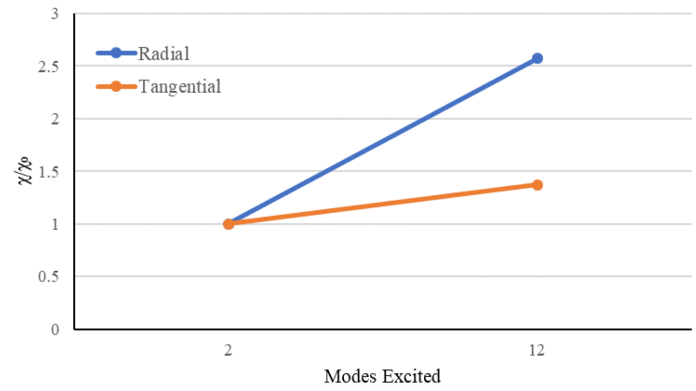


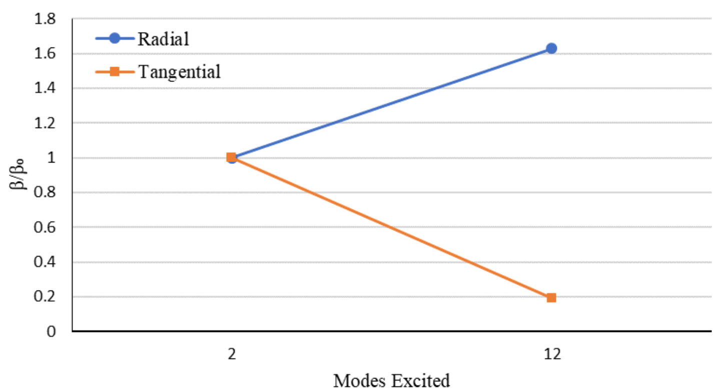
Iwan Mode 2


Mode 2 Frequency
Natural Frequency Shift [Hz]
0.5
0
-0.5
-1
-1.5
-2
M2-Experimental
M12-Experimental
M2-Iwan
M12-Iwan
10^0
10^1
Modal Acceleration at Beam Tip
Mode 2 Damping Ratio
10^{-3}
Damping Ratio
4.5
4
3.5
3
2.5
2
1.5
10^0
10^1
Peak Modal Acceleration at Beam Tip

Iwan Mode 2





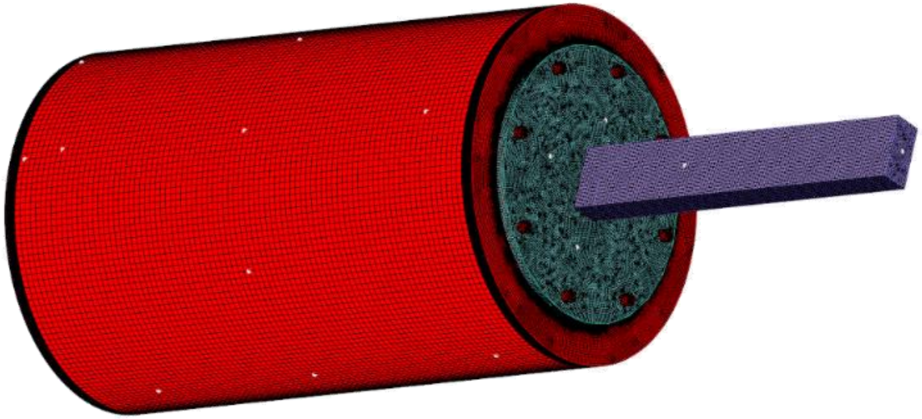


Iwan parameters for each excitation scaled against excitation of mode 2

Closing Remarks

- Mode 2 was found to couple with mode 1 when both were excited using a shaker

- Mode 1 showed a lesser degree of coupling when multiple modes were excited



- Used a high fidelity model to match nonlinear experimental data

- Iwan models, though currently incomplete, depicted the trends from the Hilbert curves

Acknowledgments

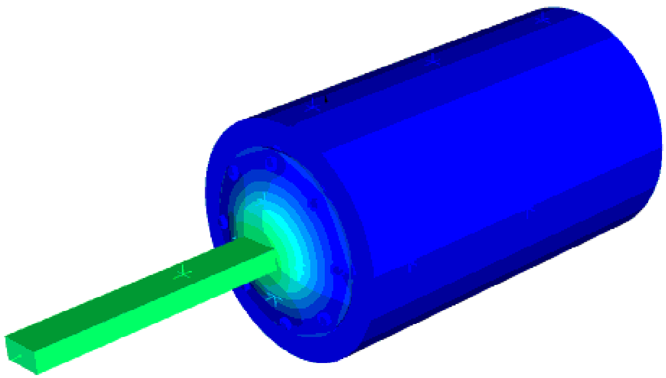
- This research was conducted at the 2018 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.

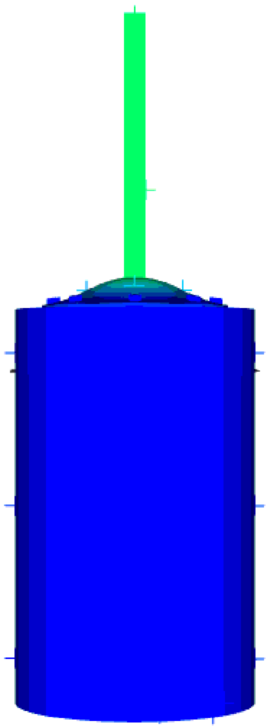
- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Appendix

Mode 3

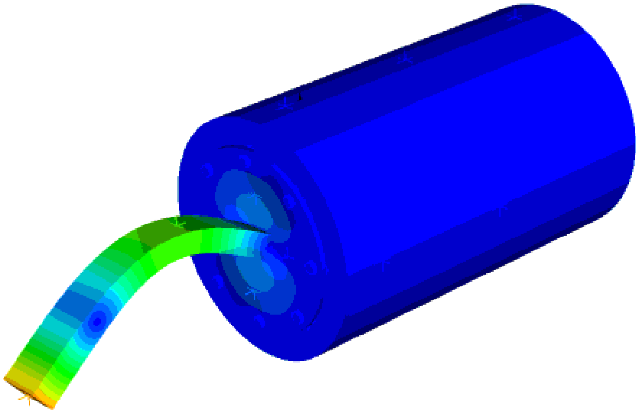
Mode Description	Experimental ω_n (Hz)
Long Plate Drum	548.43

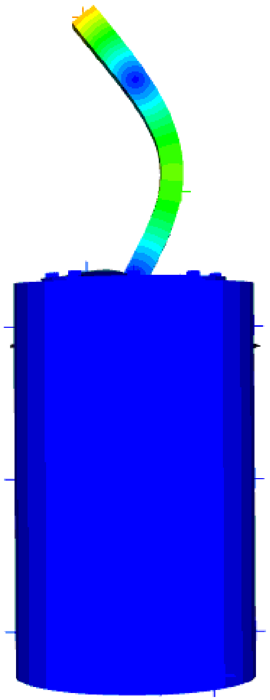




Mode 4

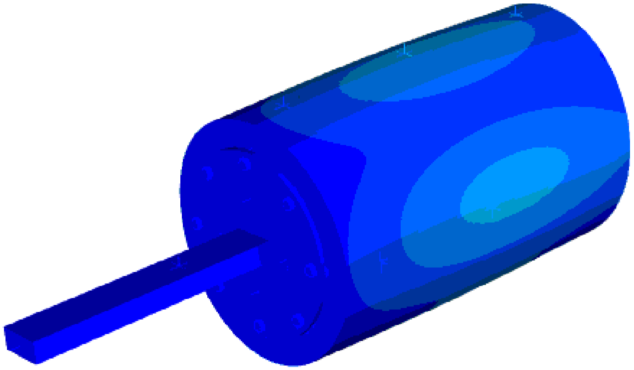
Mode Description	Experimental ω_n (Hz)
2nd Long Beam X	989.47

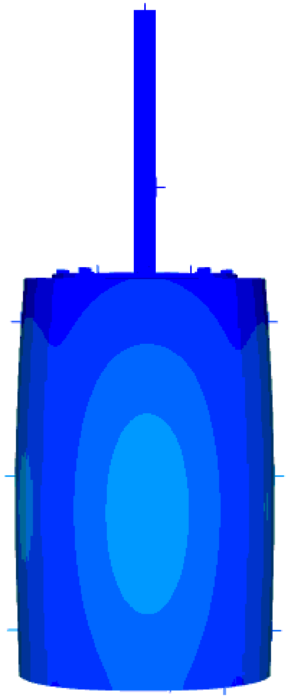




Mode 5

Mode Description	Experimental ω_n (Hz)
Ovalling	1165.1





Mode 6

Mode Description	Experimental ω_n (Hz)
Ovalling	1165.6